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Advances in research on dune-airflow-sand transport dynamics: incorporating secondary flow and sand transport processes

I. J. Walker, Department of Geography, University of Victoria, P.O. Box 3050 Station CSC, Victoria, BC, V8W 3P5 (*E-mail: ijwalker@uvic.ca*)

Introduction

The interactions between airflow, dune form and sediment transport are complex and vary over several spatial and temporal scales. Where vegetation is absent, these interactions control dune form, spacing and alignment. To date, research on windward slope airflow and sand transport dynamics is extensive (e.g., Lancaster 1985, Mulligan 1988, Frank & Kocurek 1996a, Lancaster *et al.* 1996, Wiggs *et al.* 1996, McKenna Neuman *et al.* 1997, 2000) and is reviewed elsewhere (Nickling & McKenna Neuman 1999, Wiggs 2001). Though widely cited in aeolian literature, secondary lee-side flow patterns (e.g., flow separation, reversal, deflection, shear layers, and internal boundary layer redevelopment) are poorly understood with regard to their role in transport mechanics and dune maintenance. This uncertainty relates to the complexity of lee-side flow that often precludes use of the traditional wind profile approach (i.e., the Prandtl–von Kármán equation) to predict surface shear stress and resultant sand transport. The other key impedance to progress is the lack of appropriate instrumentation for precise measurement of multi-directional and sediment-laden airflows (*see* McKenna Neuman, this volume).

This paper reviews recent research that characterizes airflow and sand transport over unvegetated, flow-transverse aeolian dunes based on extensive field, wind tunnel and flow visualization studies (*see* Walker & Nickling 2002). Several new empirical models are presented explaining the behaviour and sedimentological significance of various secondary flow phenomena including: i) macroturbulent flow regions in the lee of isolated and closely spaced dunes, ii) surface shear stress variations over idealized model dunes measured using Irwin-style pressure sensors and, iii) development and sedimentological implications of three-dimensional lee-side flow structures for dune sediment budgets and migration. Recent efforts to measure lee-side sand transport (grainfall and deflected saltation) are also discussed (e.g., Walker 1999, Nickling *et al.* 2002) and areas for future research are identified.

Discussion

To date our understanding of airflow and sand transport dynamics over transverse dunes is limited largely to the windward slope resulting in an incomplete picture of dune sediment budgets, morphodynamics, and migration. Recent research indicates however that form-generated secondary airflow patterns (e.g., streamline compression and curvature, flow acceleration, separation, reversal, deflection, turbulent shear zones) are not merely a passive consequence of flow-form interaction. Rather, they play an active role in dune dynamics and may control dune spacing and migration. Figures 1 and 2 show the two dimensional structure of secondary lee-side flow over sharp-crested dunes (Frank & Kocurek 1996b, Walker 2000). Flow is characterized by a separation cell (E) that extends 4-10h that may extend laterally to form roller or helical vortices. A wake region of less organized turbulence extends above the separation cell and dissipates downstream. The upper wake (C) consists of small vortices shed from separation that generate a steep velocity gradient overlying a slower, lower wake region (D). Detailed wind tunnel measurements (not shown) show a sharp, s-shaped profile with the boundary between C and D marked by an inflection point just above dune height. This identifies a thin shear layer that enlarges over the interdune to a shear zone (H) above flow re-attachment that may be the result of Kármán vortex streets (Walker 2000). Though the magnitude of Reynolds stress varies, the extent of H is independent of incident speed, and hence, Reynolds number. Turbulence statistics (skewness) show a balance in turbulent mixing and thus, a momentum defect level dissecting this zone caused by form drag. Vertical velocity fields show a prevalence of updrafts in the near crest region capable of suspending grains beyond typical saltation trajectories (Nickling *et al.* 2002) while downdrafts prevail within H. Over both isolated and closely spaced dunes, flow re-attachment and internal boundary layer (I) re-development are controlled by the location of the turbulent stress maximum (G) and related downdrafts in H. Because dune size determines the location and extent of E, G, H and hence, I, it is perhaps the most important control on dune spacing where sand supply is not a limiting factor.

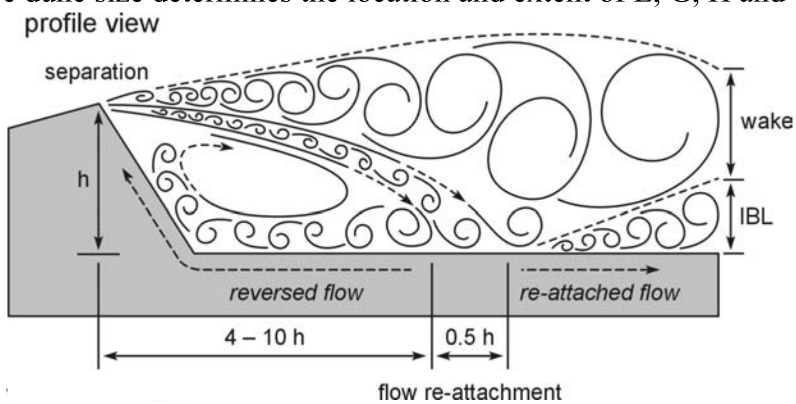

Fig. 1: Secondary lee-side flow patterns over transverse dunes (Walker & Nickling 2002).

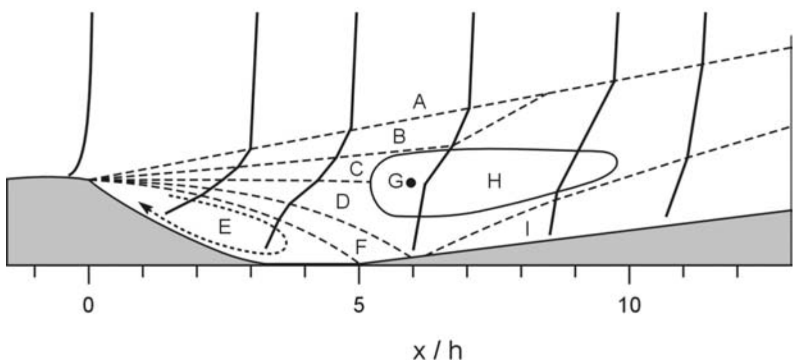

Fig. 2: Model of lee-side flow regions over closely spaced dunes (Walker & Nickling 2002).

Surface shear stress (SS) responsible for sand transport over dunes is topographically-controlled by streamline curvature (which either enhances or dampens SS if streamlines are concave or convex respectively by controlling turbulent fluctuations in the flow) and flow acceleration effects (Wiggs *et al.* 1996). For instance, concave streamline curvature at the toe conveys turbulent structures (i.e., additional turbulent stresses) toward the bed; this despite an apparent drop in profile-derived estimates of SS at this location. Convex curvature at the crest suppresses turbulence by damping vertical motions. Though the significance of curvature effects on dune dynamics is debated, for most dunes (where $h/L > 0.05$), the effects cannot be assumed negligible (Van Boxel *et al.* 1999). Figure 3 shows a model of SS over idealized dunes based on measurements using Irwin-style pressure sensors (Irwin 1981). SS declines upwind of the dune and drops rapidly at the toe due to an adverse pressure gradient, flow deceleration, and an abrupt change in flow angle. Though this implies reduced sand transport competence, a high SS variability (CVss) indicates turbulent conditions perhaps sufficient to inhibit deposition at the toe. Thus, turbulent stresses contribute to a greater and more variable SS than is apparent from time-averaged streamwise estimates alone (Wiggs *et al.* 1996, Walker 2000). Up the stoss, flow accelerates and SS rises to a maximum at the crest. Flow becomes steadier as streamlines compress and streamwise accelerations dominate the flow. Flow unsteadiness and concave curvature contribute less to SS generation with distance up the stoss *and* with incident windspeed. In the lee, SS drops significantly then increases rapidly 1-2h upwind of re-attachment; this despite flow expansion and deceleration in the separation cell. Flow visualization shows this is a result of strongly reversed surface flow. A peak in CVss at re-attachment indicates turbulent gustiness generated by separation-shed eddies impacting the surface; this causes the re-attachment point to wander by 0.5h and generates intermittent sand transport in this region (Walker 1999, McKenna Neuman *et al.* 2000). As the IBL redevelops SS increases rapidly to 12h and CVss decreases, both approaching upwind values by 25h.

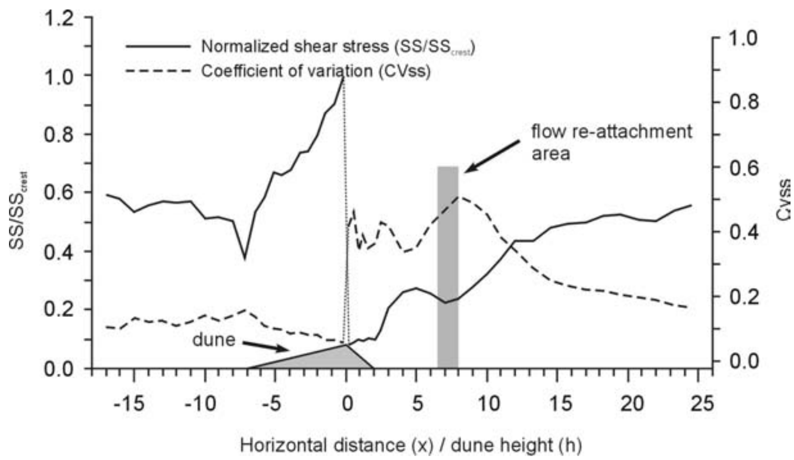

Fig. 3: Variations in SS over idealized transverse dunes (Walker 2000).

Most models of dune-airflow dynamics view the system as two-dimensional. However, secondary flows generate 3-d (reversed, deflected, lateral) mass and energy transfers that must be considered for interpretation of dune sediment budgets, dynamics and migration. Figure 4 shows lee-side flow response at different heights below the dune crest for various incident angles. This deflection mechanism explains the development of helical vortices that transport sand intermittently in saltation along the interdune corridor (Walker 1999). Deflection is greatest in the zone of maximum flow expansion and deceleration upwind of re-attachment causing the crest-parallel component to deflect flow vectors parallel to the crest differentially with height within the separation cell. As flow accelerates beyond re-attachment flow vectors and sand transport deflect back toward crest-normal. This simple mechanism explains, in part, why longitudinal flows are observed in the lee (e.g., Sharp 1966, Tsoar *et al.* 1985) and may promote oblique migration of transverse dunes under relatively transverse incident flows.

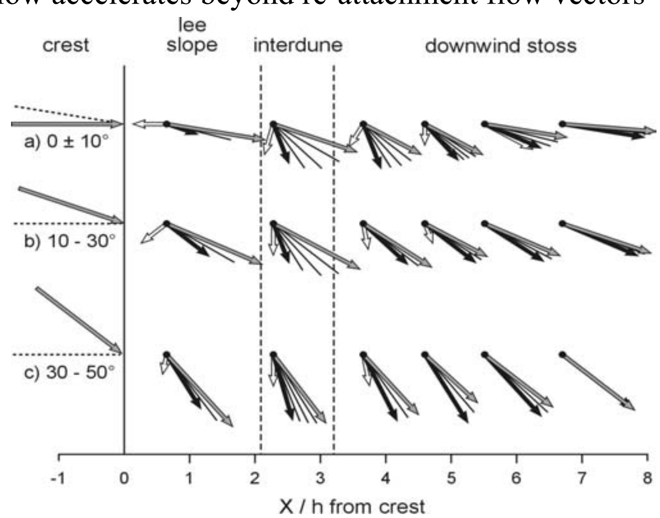

Fig. 4: Flow deflection mechanism based on detailed field measurements and flow visualization in lee of a transverse ridge (Walker 2000).

Conclusions

Recent research on airflow and sand transport over transverse dunes indicates that secondary airflow and sand transport patterns (streamline curvature, flow separation and reversal, helical vortices, shear layers, lee-side deflection) may play a significant role in dune morphodynamics. Empirical models presented here explain relations between dune form, secondary flow and sand transport that are key to dune maintenance and migration. Further validation and refinement of these models is underway to better define the significance of these process-response relations using new, higher-frequency turbulence and sand transport instrumentation. Other related areas in need of research include: more detailed field characterization of the lee-side flow field using turbulence instrumentation; further research on effects of dune size and spacing on secondary flow and sand transport; a comprehensive study of sand transport over and in the lee of dunes using more precise and higher frequency measurement of airflow saltation and grainfall; research on the effects of incident flow angle on both stoss and lee flow fields and sand transport (i.e., the 'fetch-effect') on sand transport into and over dunes.

References

Frank, A. & G. Kocurek. 1996a. Airflow up the stoss slope of sand dunes: limitations of current understanding. *Geomorphology*, **17**: 47-54.

Frank, A. & G. Kocurek. 1996b. Toward a model of airflow on the lee side of aeolian dunes. *Sedimentology*, **43**: 451-458.

Irwin, H.P.A.H. 1981. A simple omnidirectional sensor for wind tunnel studies of pedestrian level winds. *Journal of Wind Engineering and Industrial Aerodynamics*, **7**: 219-239.

Lancaster, N. 1985. Variations in wind velocity and sand transport rates on the windward flanks of desert sand dunes. *Sedimentology*, **32**: 581-593.

Lancaster, N., W.G. Nickling, C. McKenna Neuman & V.E. Wyatt. 1996. Sediment flux and airflow on the stoss slope of a barchan dune. *Geomorphology*, **17**: 55-62.

McKenna Neuman, C. 2002. The role of instrumentation in aeolian research: recent advances and future challenges. In: *Joint meeting of the International Conference on Aeolian Research (ICAR5) and The Global Change & Terrestrial Ecosystem-Soil Erosion Network (GCTE-SEN), Texas Tech. University, Lubbock, Texas, 22-25 July 2002.*

McKenna Neuman, C., N. Lancaster & W.G. Nickling. 1997. Relations between dune morphology, air flow, and sediment flux on reversing dunes, Silver Peak, Nevada. *Sedimentology*, **44**: 1103-1113.

McKenna Neuman, C., N. Lancaster & W.G. Nickling. 2000. The effect of unsteady winds on sediment transport on the stoss slope of a transverse dune, Silver Peak, NV, USA. *Sedimentology*, **47**: 211-226.

Mulligan, K.R. 1988. Velocity profiles measured on the windward slope of a transverse dune. *Earth Surface Processes and Landforms*, **13**: 573-582.

Nickling, W.G. & C. McKenna Neuman 1999. Recent investigations of airflow and sediment transport over desert dunes. In: *Aeolian Environments, Sediments and Landforms* (Eds Goudie, A.S., Livingstone, I. and Stokes, S.), pp. 15-47. John Wiley & Sons, Chichester.

Nickling, W.G., C. McKenna Neuman & N. Lancaster. 2002. Grainfall processes in the lee of transverse dunes, Silver Peak, Nevada. *Sedimentology*, **49**: 191-209.

Sharp, R.P. 1966. Kelso Dunes, Mohave Desert, California. *Geological Society of America Bulletin*, **77**: 1045-1074.

Tsoar, H., K.R. Rasmussen, M. Sørensen & B.B. Willetts 1985. Laboratory studies of flow over dunes. In: Barndorff-Nielsen, O.E., Møller, J.T., Rasmussen, K.R. and Willetts, B.B. *Proceedings of International Workshop on the Physics of Blown Sand, Aarhus,* 327-350.

Van Boxel, J.H., S.M. Arens & P.M. Van Dijk. 1999. Aeolian processes across transverse dunes. I: modelling the air flow. *Earth Surface Processes and Landforms*, **24**: 255-270.

Walker, I.J. 1999. Secondary airflow and sediment transport in the lee of reversing dunes. *Earth Surface Processes and Landforms*, **24**: 437-448.

Walker, I.J. 2000. *Secondary airflow and sediment transport in the lee of transverse dunes*. Ph.D., University of Guelph, Guelph, 256 pp.

Walker, I.J. & W.G. Nickling. 2002. Dynamics of secondary airflow and sediment transport over and in the lee of transverse dunes. *Progress in Physical Geography*, **26**: 47-75.

Wiggs, G.F.S. 2001. Desert dune processes and dynamics. *Progress in Physical Geography*, **25**: 53-79.

Wiggs, G.F.S., I. Livingstone & A. Warren. 1996. The role of streamline curvature in sand dune dynamics: evidence from field and wind tunnel measurements. *Geomorphology*, **17**: 29-46.